FAILURE CRITERIA FOR BLAST LOADS STRUCTURES - A REVIEW

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INTRODUCTION

The reliable rating of protective structures in a blast environment depends to a large extent on the ability to predict the magnitude and duration of the blast load required to produce incipient collapse. Such ability is best developed on the basis of experimental data on the failure of structures. At the present time experimental data on this subject is very limited. Also, the field of predicting incipient collapse of structures is mostly in its infancy.

This paper briefly reviews the state-of-the-art of predicting the incipient collapse of structures subjected to blast loads and presents a suggested experimental and analytic, probability based program capable of producing the required data and criteria by the use of full-scale tests and model studies. The emphasis of this review is on reinforced concrete structures.

REVIEW OF EXPERIMENTAL WORK

The interest in the behavior of structures when subjected to high intensity blast loads had its beginning shortly after the detonation of the first nuclear device. In the 1950's, a series of nuclear weapon field tests was conducted. The specimens were full-scale structures, scale model structures and structural components. The emphasis was on the development of reliable and economical design and analysis methods for protective construction. These tests produced a wealth of data. Among other things, it was demonstrated that structures located below the ground surface, even in a shallow burial, survived significantly better than those directly exposed to the blast. In fact many of the buried structures (including conventional basements) survived at surface overpressures several times the specified design overpressure. This first series of tests also demonstrated a need for further tests, and the need to develop analytic methods capable of simulating actual structural response to blast loads.

Since these early tests a great deal of additional work has been devoted to the simulation of weapon effects, mostly in the laboratory (2-13). Concurrently with experimental studies, research upon the development of analytic methods aimed at predicting structural response was initiated (14-20). Field tests are still being conducted on a periodic basis. These, however, are less extensive in scope than the previous test series. Loading is usually produced using conventional exposives simulating a low yield nuclear device. Also, most of the current tests conducted are mainly in the category of proof tests.

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The development of reliable and economic design methods requires accurate knowledge of the loads (intensities and distributions) experienced by a given structure and the conditions leading to collapse (i.e. failure criteria). Yield line theory (21) is extensively used to predict the collapse loads of reinforced concrete slabs. This theory has proved to be effective in predicting the initial loads causing hinges to form for slabs with negligible membrane forces. However, such slabs are relatively uncommon in actural hardened construction. Roof and wall slabs are generally restrained to some degree and the yieldline approach therefore, is only partially applicable. The importance of restraint on slab load carrying capacity has been studied by a number of investigators both within and outside the defense community (2,3,22-31). It has been demonstrated that in laterally restrained slabs two types of membrane action may occur. Compressive membrane action, the so-called arching effect, occurs at the early stages of deflection. This is then followed by tensile membrane action at more advanced stages of loading. Arching action is produced because compressive forces at the center of the slab act above the slab mid-depth. Compressive forces thus follow the pressure line of a shallow arch. Due to this action, the load-carrying capacity of the slab may well be substantially greater than that predicted by yield-line theory. As the deflection of the slab increases further, cracking of the concrete occurs and the membrame action in the central region shifts from compressive to tensile. Thereafter, the slab carries load by the reinforcement acting as a plastic tensile membrane, with cracking penetrating the slab thickness. The ultimate tensile membrane capacity is reached when the reinforcement is at incipient rupture. The load-displacement relationship (resistance function) depends on the degree of restraint along the edges, the quantity of reinforcement and extent to which the reinforcement is embedded beyond the slab boundaries.

The incipient collapse of a reinforced concrete slab is generally related to its midpoint deflection. This failure deflection, δ_u, is empirically expressed as a function of the short-direction span length of the slab. For example, Park (22) and Keenan (2) suggest that $\delta_u = 0.1\ell_s$, where ℓ_s is the short direction span length. Black (3), calims that this value is too conservative and suggests that $\delta_u = 0.15\ell_s$. Herzog (23) suggests that $\delta_u = 0.31\ell_s\sqrt{\varepsilon_u}$ where ε_u is the rupture strain of reinforcement. A Portland Cement Association study (27) suggests that $\delta_u = k\ell_s\sqrt{\varepsilon_u}$ where k is a factor which accounts for the non-uniform distribution of strain along the length of the reinforcing bars.

These failure criteria apply to a fully restrained condition and are assumed to be independent of concrete strength and slab geometry. Two-way action in the slab is neglected and no distinction is made between static and dynamic loads. Obviously a great deal of research remains to be done in this area.

Certain types of slabs, by virtue of their size, type of support conditions and loading, will fail primarily in shear. Certain column supported slabs are in this category and many types have been studied with respect to conventional static loads. Data that can be used to define a dynamic resistance function for reinforced concrete slabs are very limited (32-36). For building construction, the primary interest is in the peak shear capacity and, therefore, no attempt has been made in tests to determine post peak behavior of members failing in shear or flexure. Failure analyses make use of the modified ACI formula (37) when considering shear as a mode of failure. Some recent studies performed at NCEL (38) have used shear ductility in the analysis of dynamically loaded reinforced concrete slabs. In this approach it is assumed that prior to shear failure a shear hinge is formed analogous to the formation of a plastic hinge prior to flexural failure. This failure criterion is also very tentative.

Structural members such as columns, beam-columns, slabs subjected to lateral and in-plane loads, shear walls (39-42), structural assemblies (43,44), connections (45), etc. have received very little attention as far as incipient collapse is concerned. Some full-scale structures have been tested and these test data do exist (1). This includes arches and rectangular structures both buried and above ground. However, these appear as mostly special cases in terms of load environment and type of structure. Very little duplication of experiments for control purposes has been performed.

SUGGESTED RESEARCH

After some thirty years of testing in the field and the laboratory, widely acceptable failure criteria for structures subjected to blast loads do not exist. The need to develop failure criteria still exits.

A coordinated, long-term experimental-analytic study aimed at the development of failure criteria for structures subjected to dynamic loads is recommended. It should involve the following topics:

1. A review and categorization of all pertinents experimental data.

2. The development of an experimental plan to include full-scale structures, scale model structures and individual components.

3. A comparison of test results with predictions of behavior using analytic statistical-probabilistic techniques.

It is important to emphasize that a long-term coordinated (five to ten years) effort is recommended. The major failure of the studies performed during the past thirty years was the lack of continuity and coordination between the individual studies. Since both the Department of Defense and non-defense related agencies would benefit from such an effort, it is recommended that a multi-agency program be set up to pursue the stated objectives.

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